A phase-one LHC luminosity upgrade based on Nb-Ti

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CONTENTS

- Goals of a phase one luminosity upgrade
- A flow-chart for determining triplet parameters
- Limits to long (and large) triplets
- Geometric aberrations
- Issues in magnet design

Most of the presented material has been published in *LHC Project Report* **1000** (2007)
A paper with issues related to magnet design will be presented in PAC07 (F. Borgnolutti, E. Todesco)
A paper about the accelerator physics issues for the phase-two upgrade will be presented in PAC07 (J.P. Koutchouk et al)

GOALS OF A PHASE-ONE UPGRADE

- Staging the LHC luminosity upgrade in two phases
  - Phase one (asap – for ultimate or recovery)
    - Aim: not more than ultimate luminosity ($\sim 2.5\times10^{34}$ cm^{-2} s^{-1}), or ways to recover nominal ($\sim 1\times10^{34}$ cm^{-2} s^{-1}) in case that some parameters are not met
    - No modification of detectors – minimal lay-out modifications (D1)
    - Larger aperture triplet to reduce part of the limit on intensity due to collimators (presently 40% of nominal, or $\beta^*\sim 0.9$ m instead of 0.55 m)
    - Larger aperture to have stronger focusing with some margin ($\beta^*\sim 0.25$ m, $L\sim 1.5\times10^{34}$ cm^{-2} s^{-1})
    - Fast: use Nb-Ti quadrupoles with available cable
  - Phase two (the 'real' upgrade)
    - Aim at 10×10^{34} cm^{-2} s^{-1}
    - Upgrade of detectors to tolerate it (6-12 months shut-down ?)
    - Use Nb_3Sn to better manage energy deposition and have shorter triplet allowing reaching a 30% lower β^*
    - Crab cavities or D0 to reduce effect of crossing angle
    - … all other possibilities analysed up to now in CARE-HHH and LARP

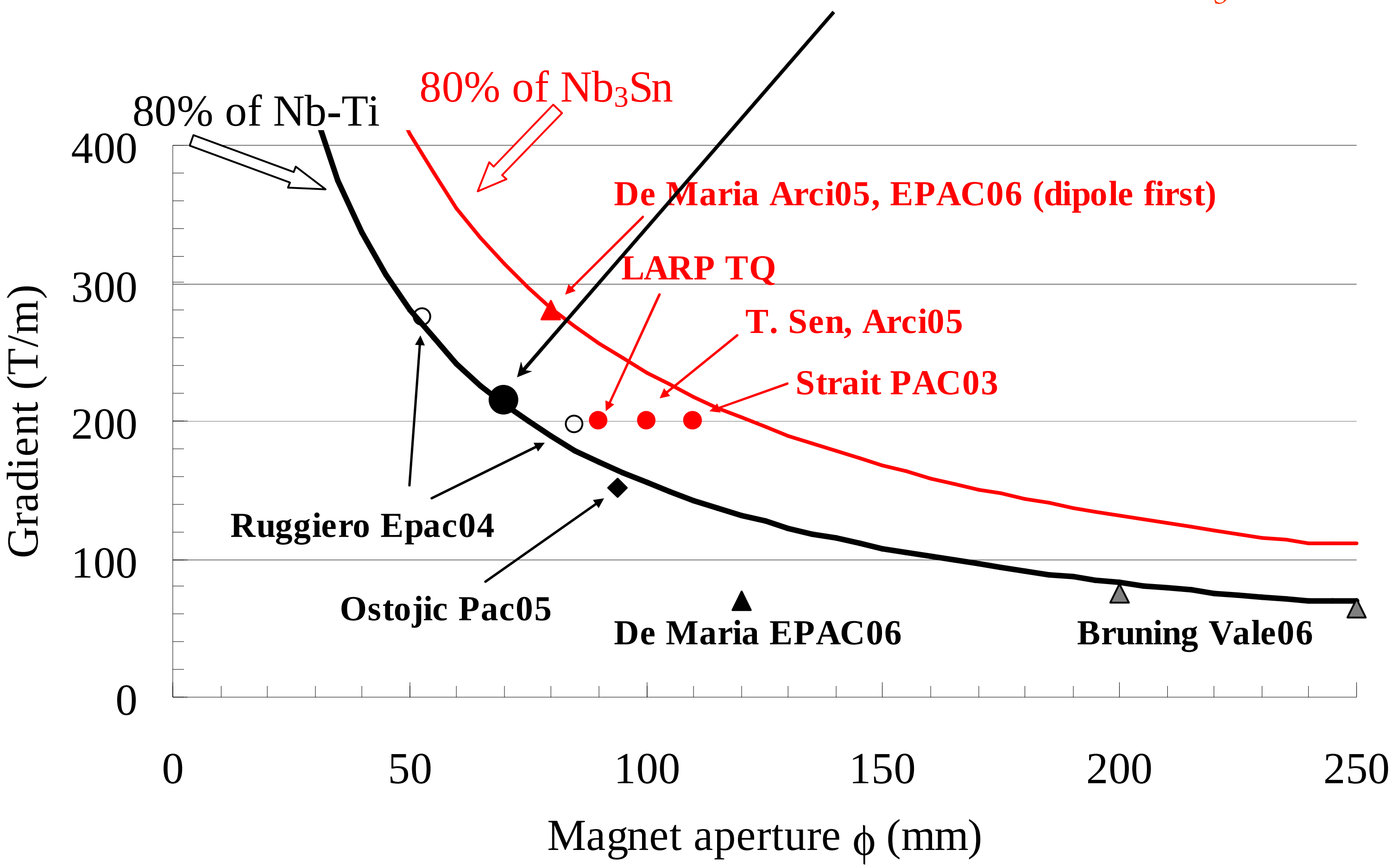
GOALS OF A PHASE-ONE UPGRADE: METHODS AND TOOLS

- Several works have been carried out since 2002 both on the optics and on the magnets
- A large effort to have parametric analysis ("scaling laws") has been done since 2004
    - In the spirit of the work on the dipoles carried out in LARP [S. Caspi, P. Ferracin, S. Gourlay, in PAC05 and ASC06] , and in the 90's by Rossi et al. in LASA
  - This allows having a global view on the parameter space to find the optimum – what we did:
    - Technological limit: gradient vs aperture in Nb-Ti and Nb_3Sn quadrupoles [L. Rossi, E. Todesco, *Phys. Rev. STAB* **9** (2006) 102401]
    - Field quality: multipoles versus quadrupole aperture [B. Bellesia, J. P. Koutchouk, E Todesco, *Phys. Rev. STAB* **10** (2007) 062401]
    - Forces: stresses versus quadrupole aperture and coil width [P. Fessia, F. Regis, E. Todesco, ASC06, *IEEE Trans. Appl. Supercond.* in press]
    - Optics: Quadrupole aperture versus triplet length, β^* , distance to IP, sc material [E. Todesco, J. P. Koutchouk, Valencia06 proceedings]

GOALS OF A PHASE-ONE UPGRADE

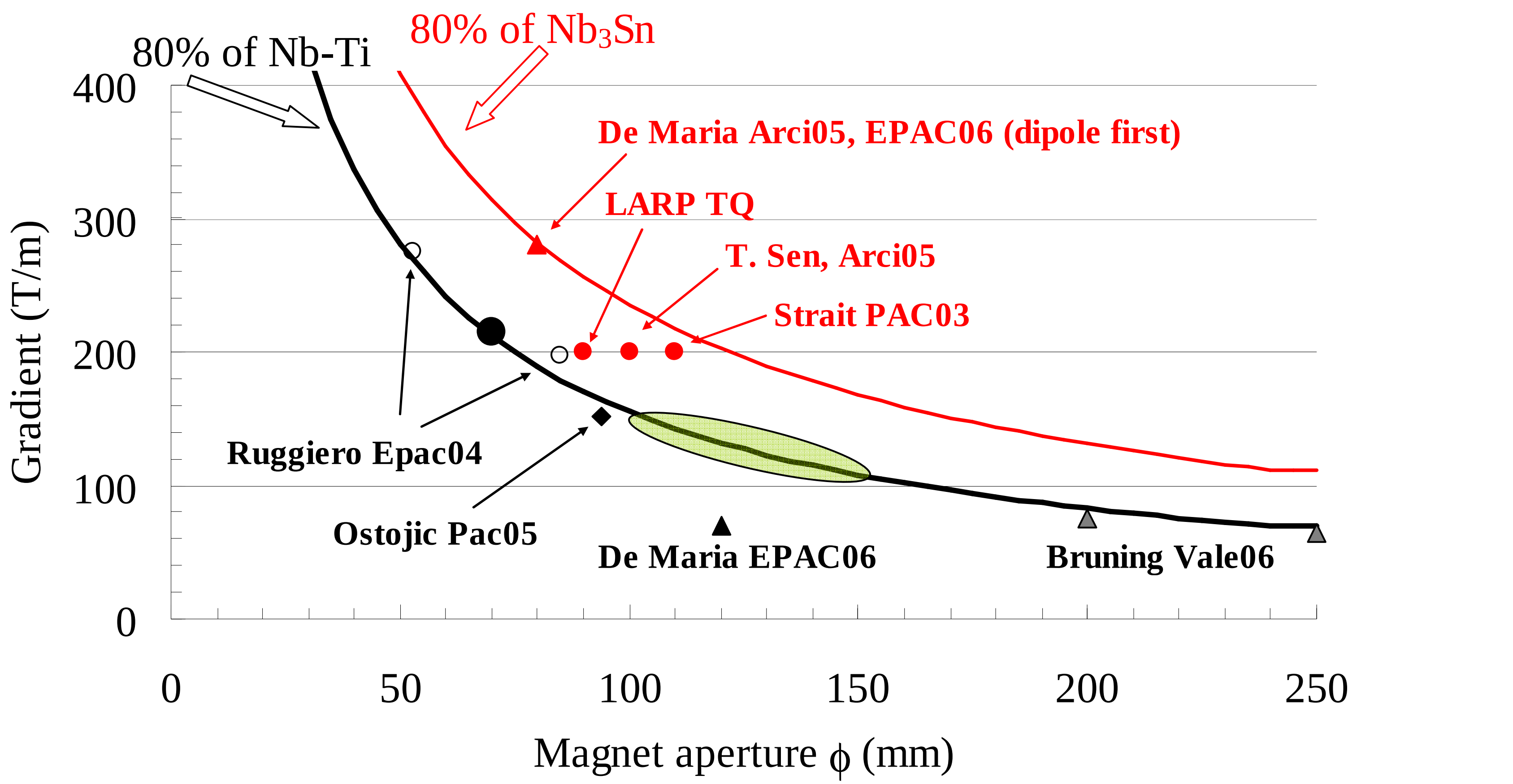
- Tentative summary of previous optics lay-outs to go to $\beta^* = 0.25$ m

Nb-Ti: black baseline Nb_3Sn: red



GOALS OF A PHASE-ONE UPGRADE

- We will explore the region between 100 and 150 mm, at the limit of Nb-Ti



GOALS OF A PHASE-ONE UPGRADE: MAIN RESULTS

- The analysis of the aperture requirements for β^*=0.25 m shows that
  - 90 mm are not enough
  - this comes from several factors (collimation, optics, beam dynamics …)
  - 130 mm is a reasonable choice
  - 130 mm allow to ease the beam dynamics (lower aberrations)

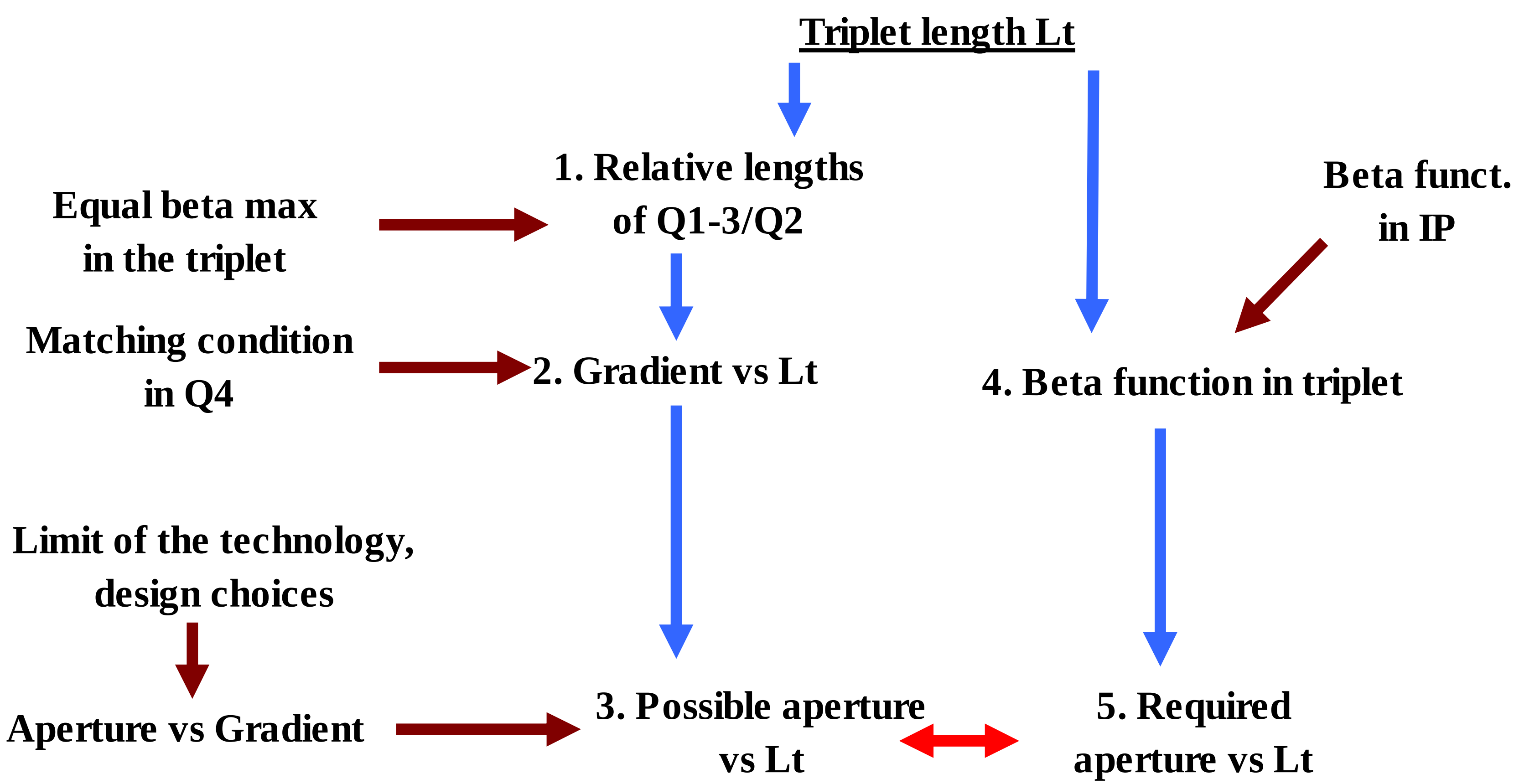
- One can obtain a β^*=0.25 m with Nb-Ti by making a triplet 10 m longer
  - This involves moving the separation dipole (D1) 10 m further away from the IP
  - This changes the goal of 200 T/m, which was related to the triplet length

- In the followings, I will outline the main motivations behind these choices

CONTENTS

- Goals
- A flow-chart for determining triplet parameters
- Limits to long (and large) triplets
- Geometric aberrations
- Issues in magnet design

A FLOWCHART FOR TRIPLET PARAMETERS



A FLOWCHART FOR TRIPLET PARAMETERS

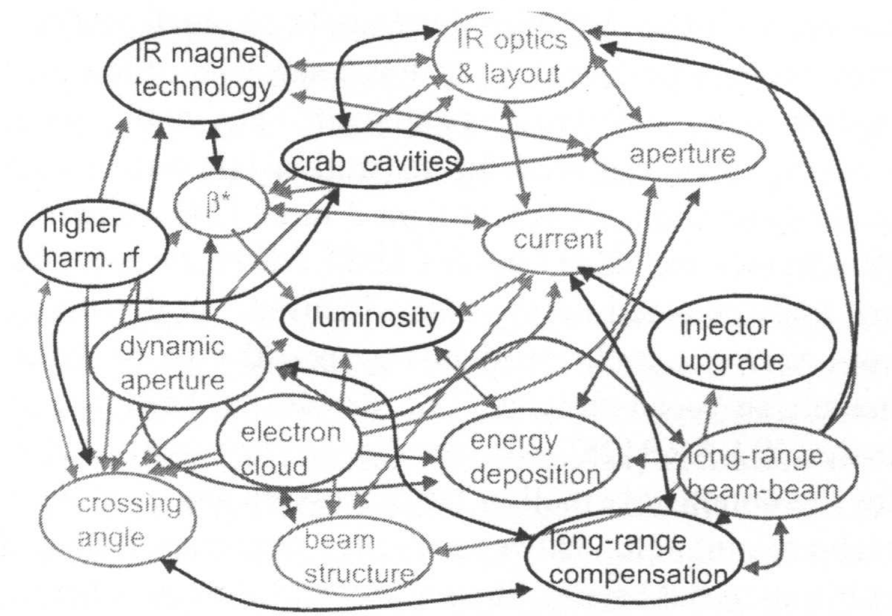
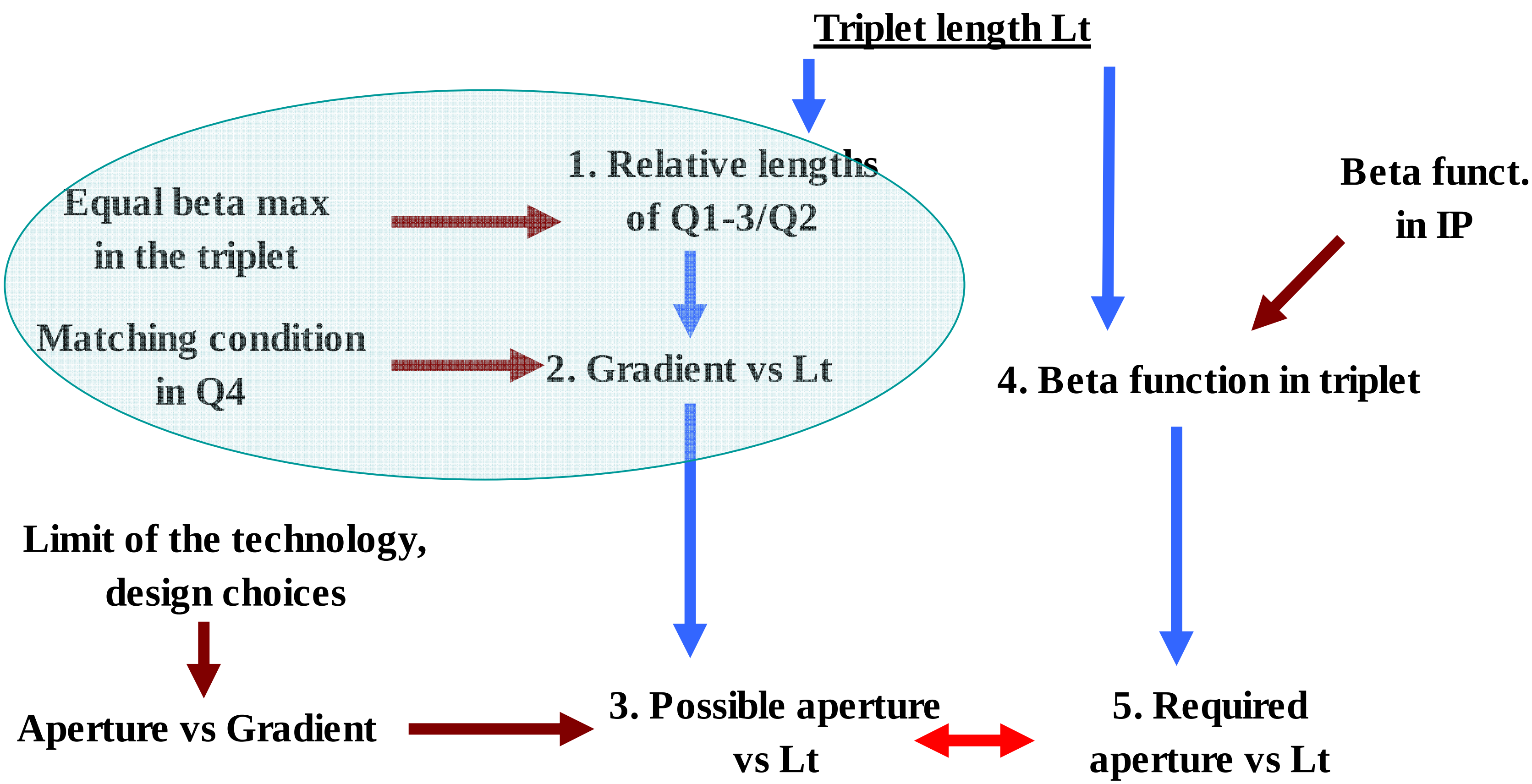


Figure 2: Upgrade roadmap for the LHC IR showing complex interdependence.

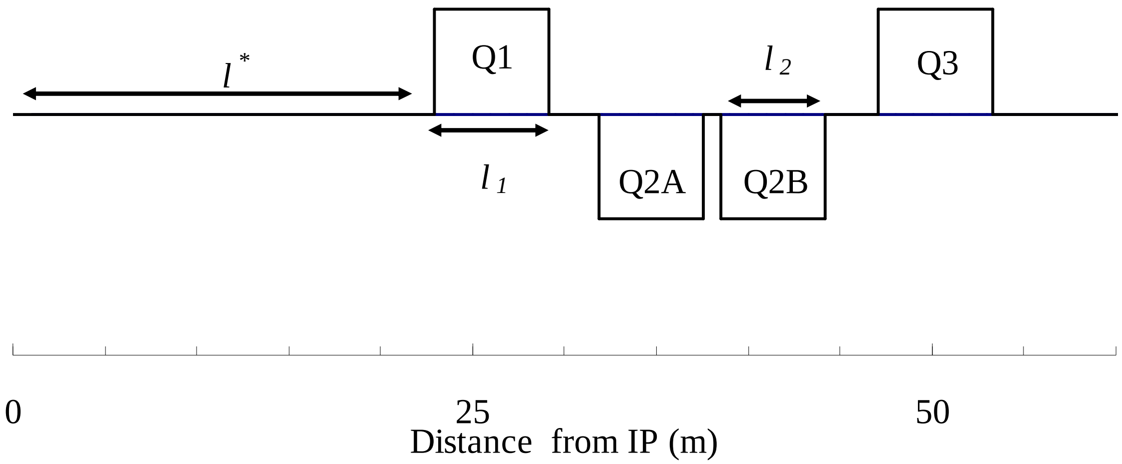
[F. Zimmermann, HB2006]

A FLOWCHART: OPTICS REQUIREMENTS



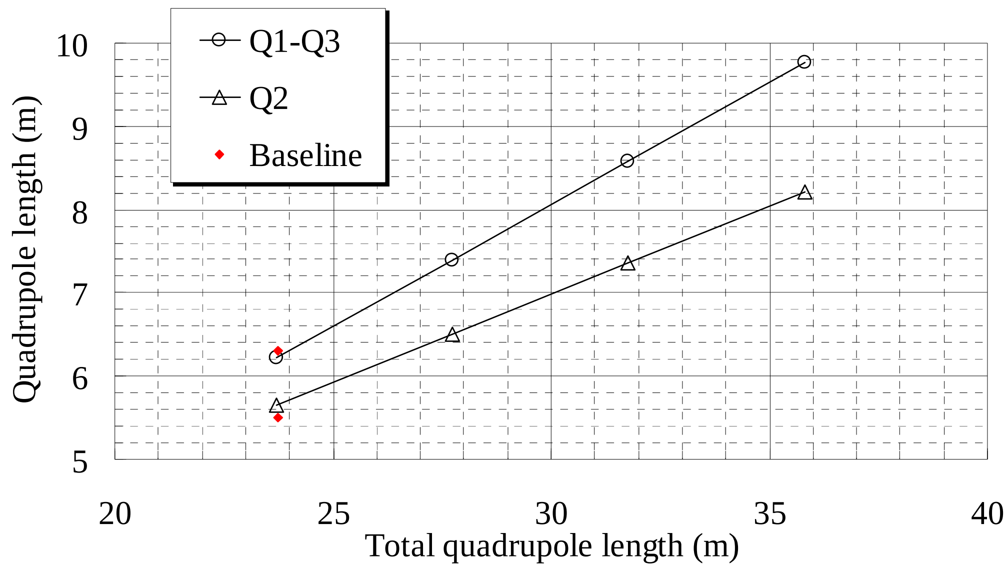
A FLOWCHART: OPTICS REQUIREMENTS

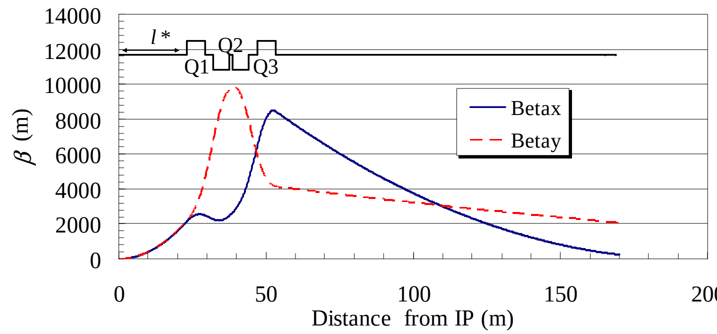
- Triplet structure
  - We fix the distance to the IP to the nominal value of 23 m
  - We fix the gaps between magnets to nominal values
  - We keep the same gradient in all magnets
  - Two magnet lengths as free parameters: Q1-Q3 and Q2
  - We explore triplet lengths from 25 m to 40 m



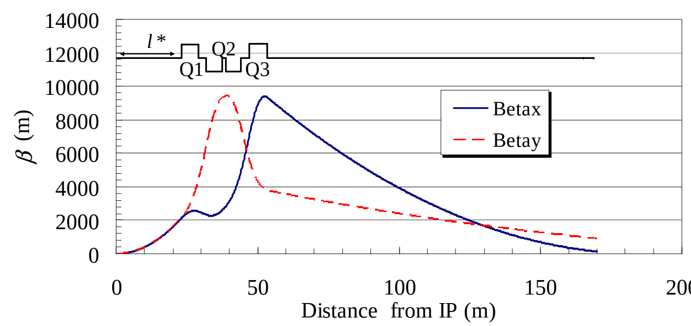
- How to fix the relative lengths of Q1-Q3 and Q2
  - For each total quadrupole length there is a combination of lengths that gives equal beta function in the two planes
  - We compute four cases, and then we fit

[E. Todesco, J. P. Koutchouk, Valencia06]





Nominal triplet l1=5.50 m l2=6.37 m

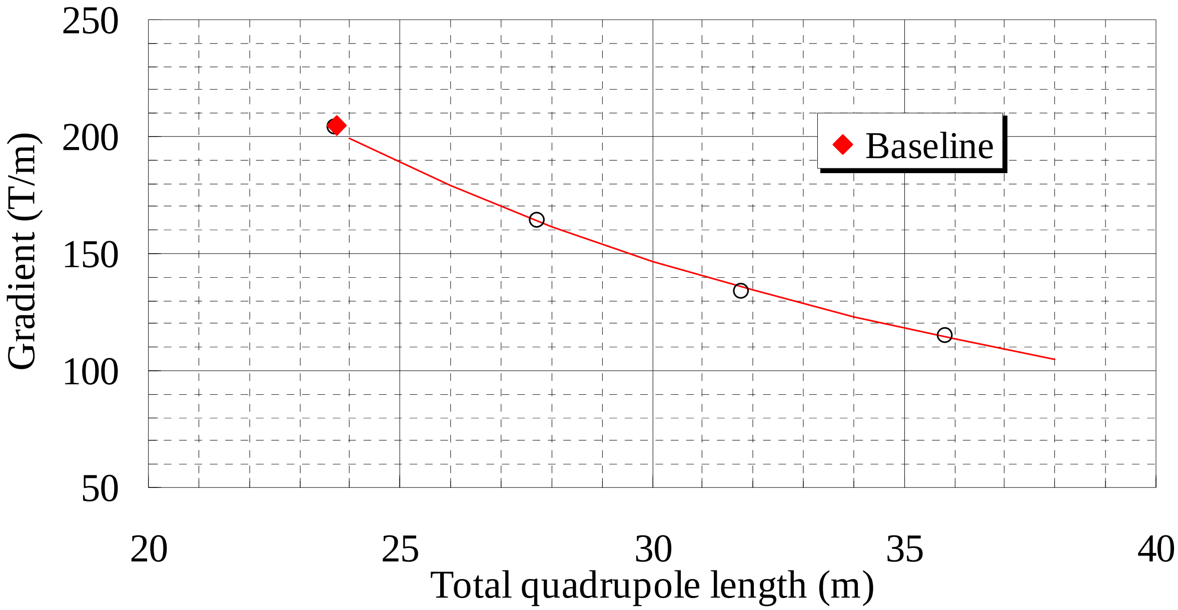


Triplet l1=5.64 m l2=6.22 m

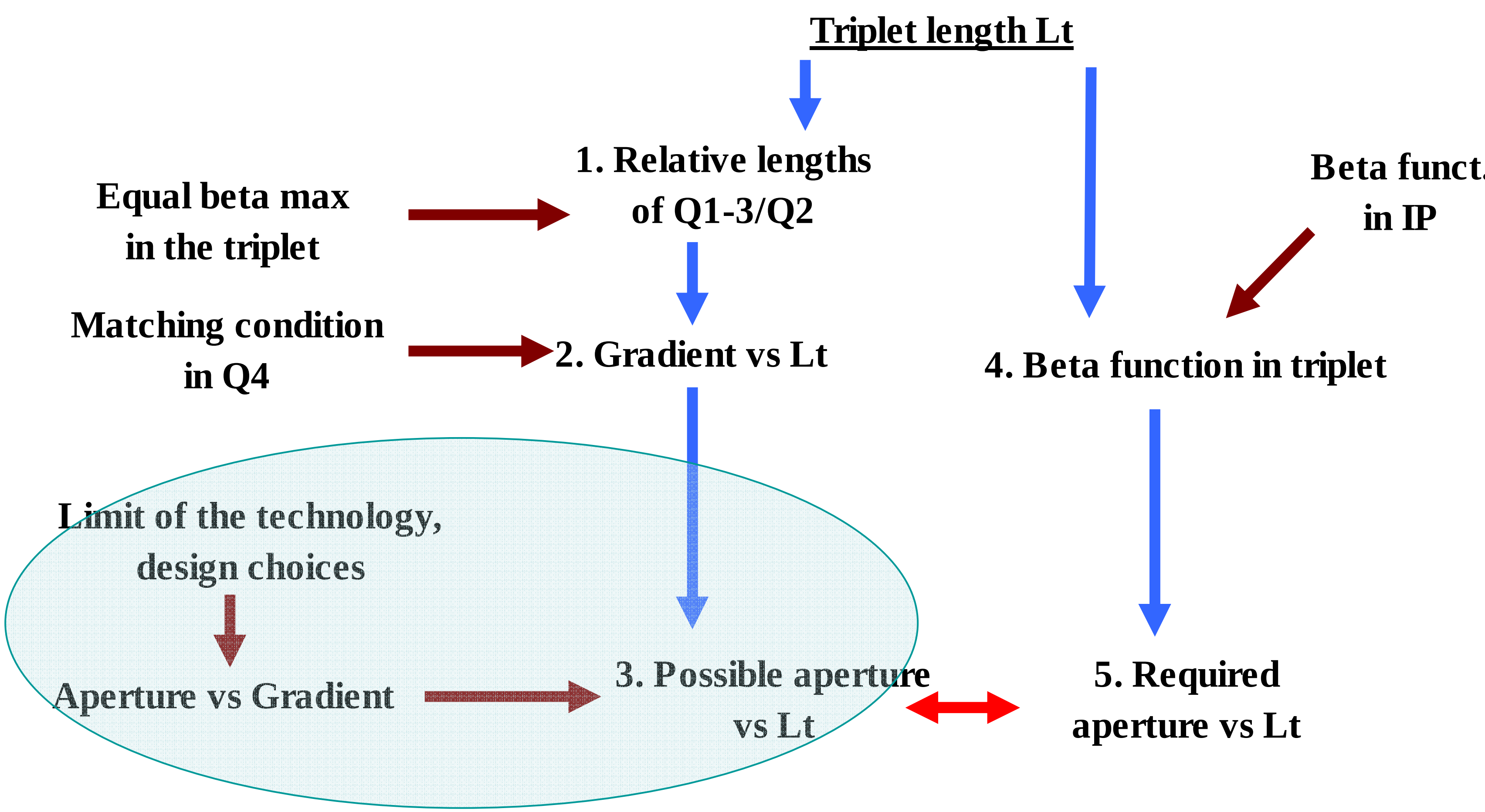
A FLOWCHART: OPTICS REQUIREMENTS

- How to fix the gradient
  - This depends on matching conditions
  - We require to have in Q4 "similar" beta functions to the nominal
  - We find an empirical fit of the four cases

$$G = \frac{1}{f l_q^2 + h l_q}$$

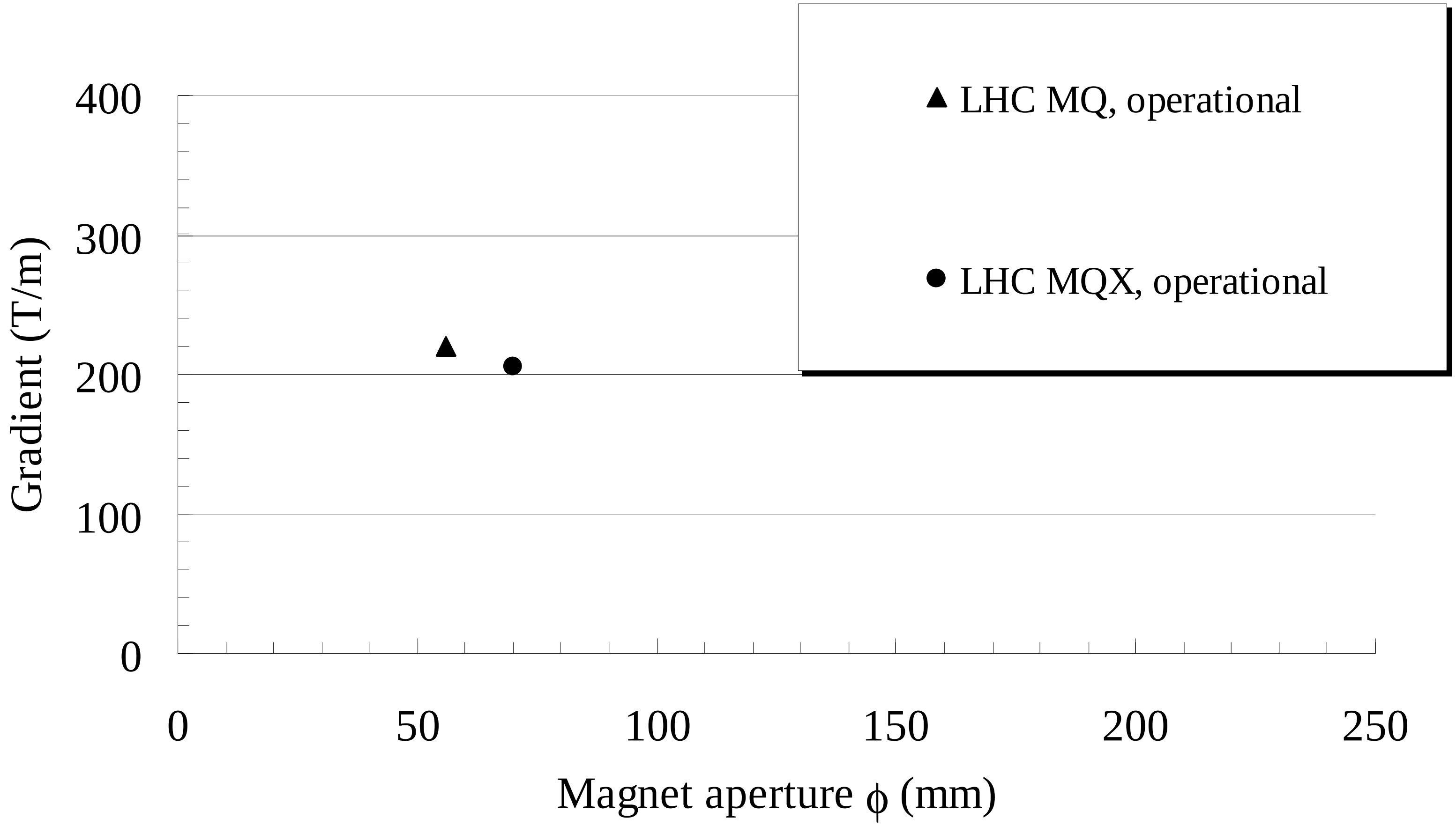


A FLOWCHART: TECHNOLOGY LIMITS



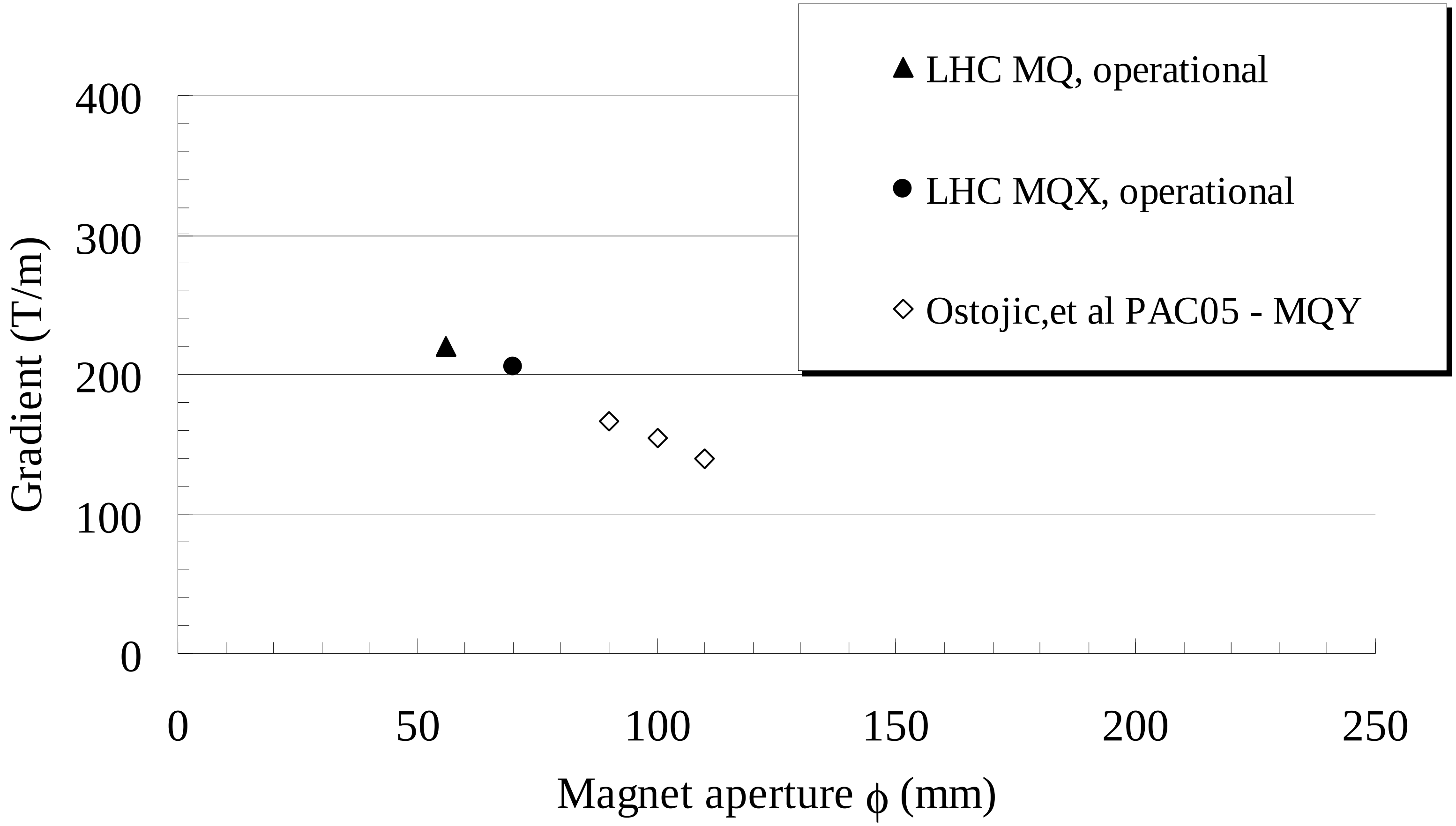
A FLOWCHART: TECHNOLOGY LIMITS

- The technology imposes a relation gradient-aperture
  - Values for some LHC quadrupoles



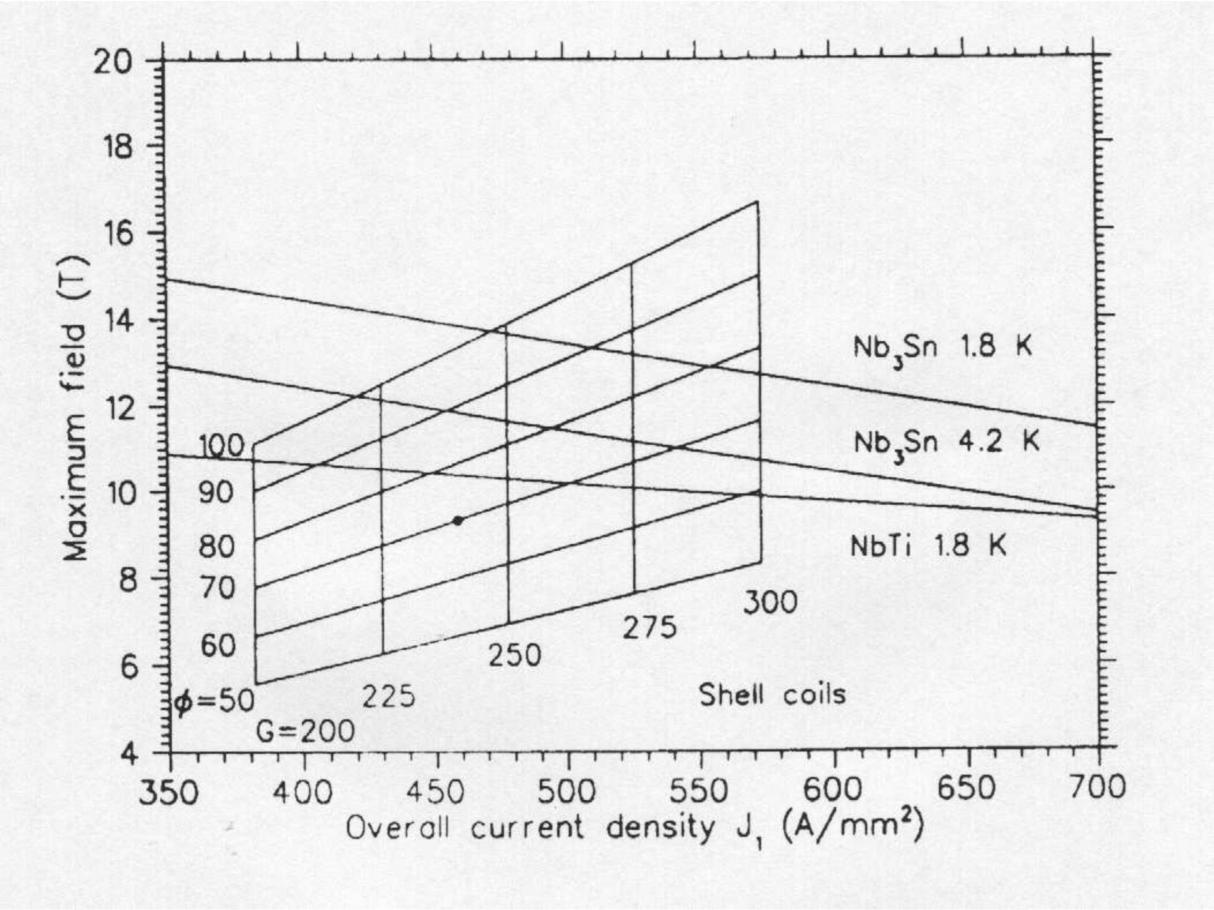
A FLOWCHART: TECHNOLOGY LIMITS

- Nb-Ti lay-outs for apertures 90 to 110 mm (MQY cable)
  [R. Ostojic, et al, *PAC05*]



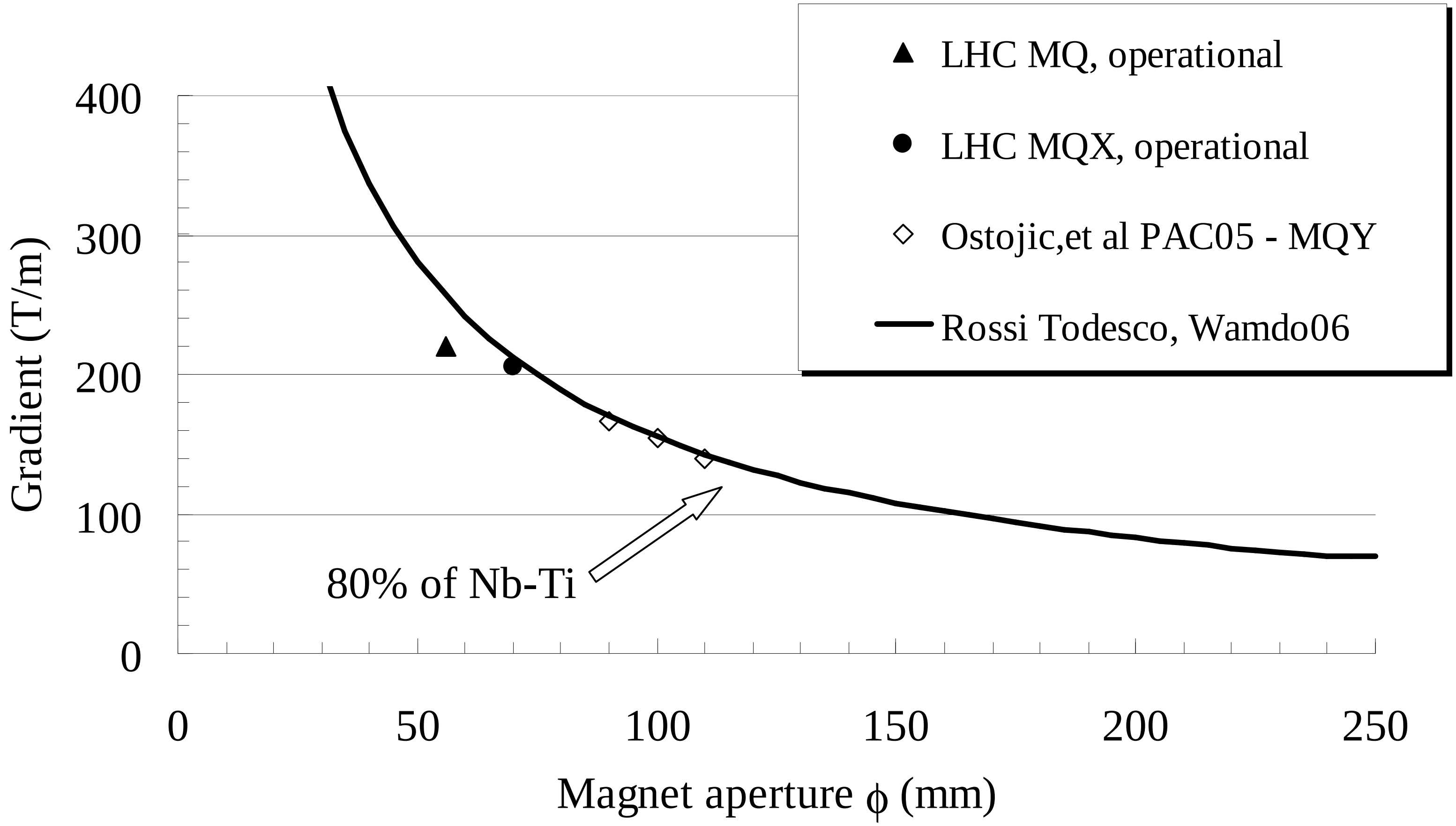
A FLOWCHART: TECHNOLOGY LIMITS

- First scaling laws estimates date back to the 90's
  [L. Rossi, et al, *INFN-TC 112* (1994)]



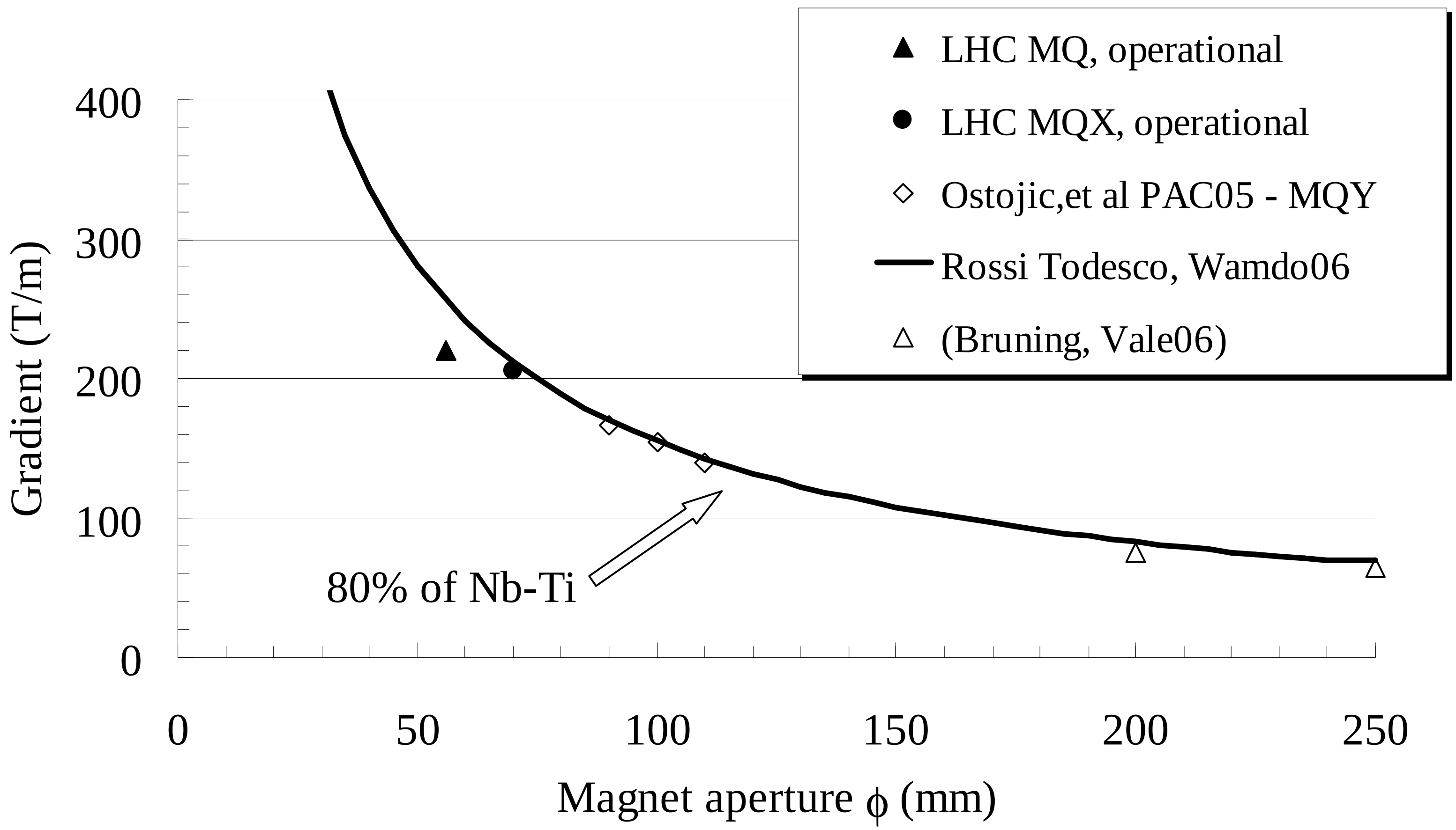
A FLOWCHART: TECHNOLOGY LIMITS

- A semi-analytical formula has been proposed for [Nb_3Sn and] Nb-Ti
  [L. Rossi, E. Todesco, *Phys. Rev. STAB* **9** (2006) 102401]



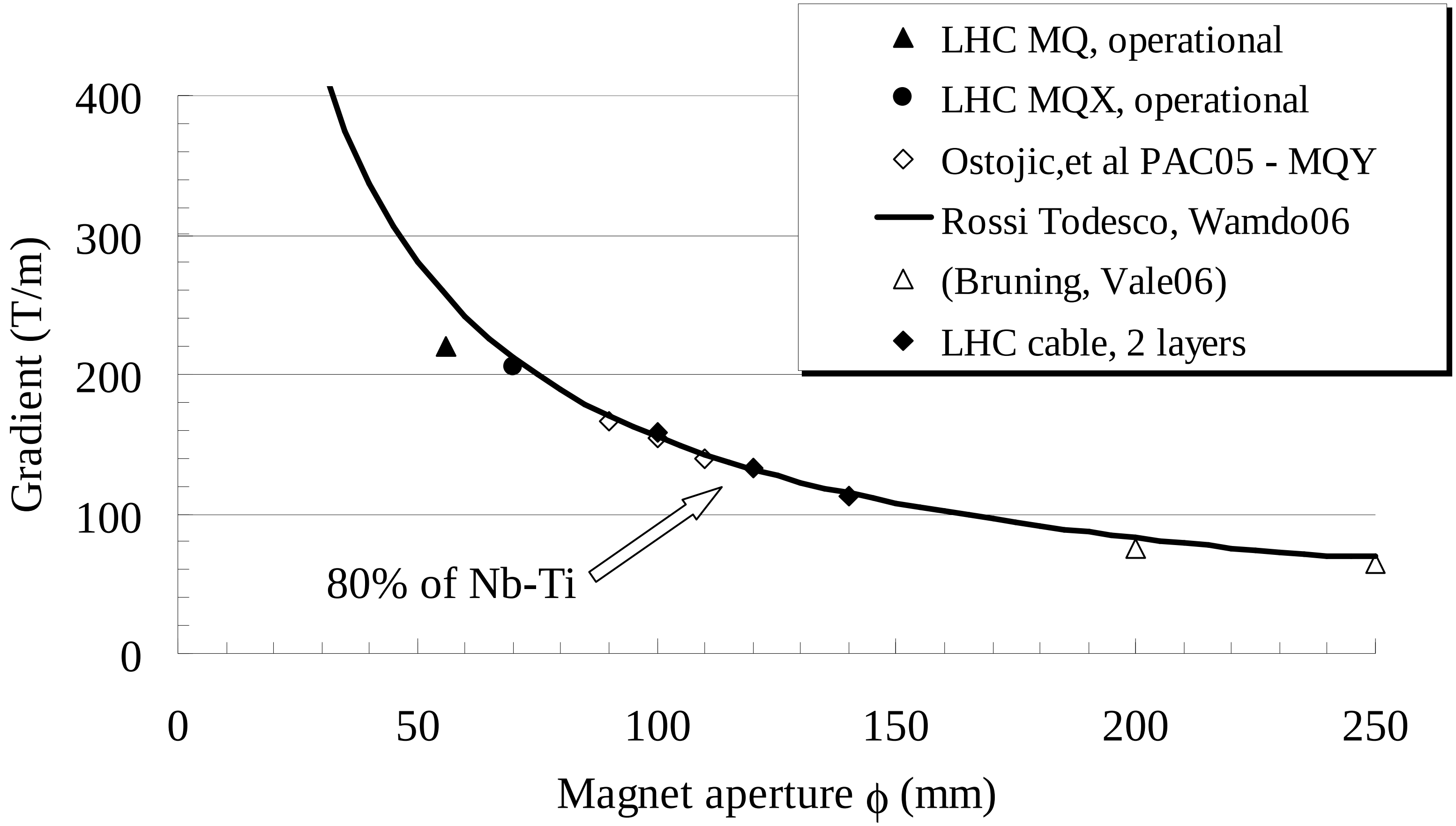
A FLOWCHART: TECHNOLOGY LIMITS

- Assumption for low gradient, very long triplet
  [O. Bruning, R. De Maria, Valencia workshop 2006]



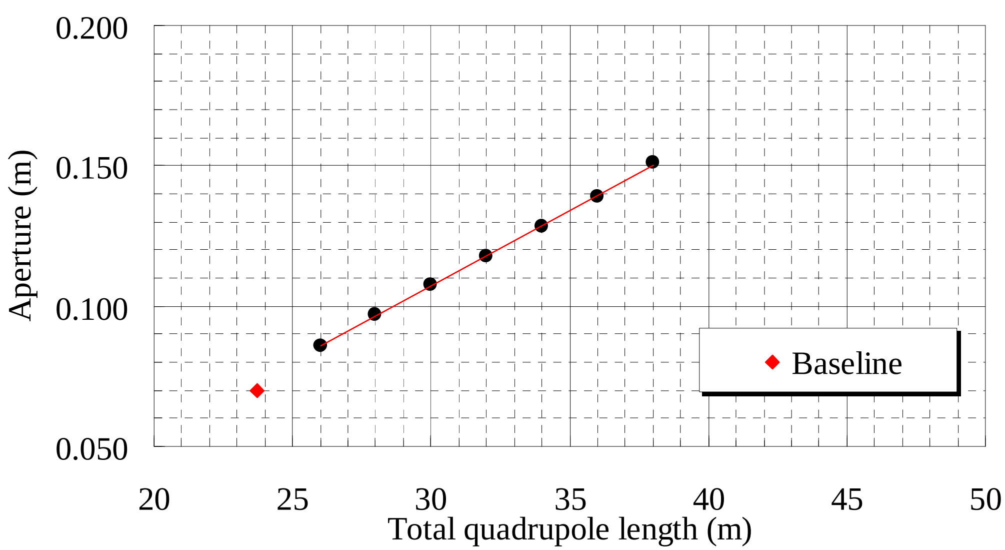
A FLOWCHART: TECHNOLOGY LIMITS

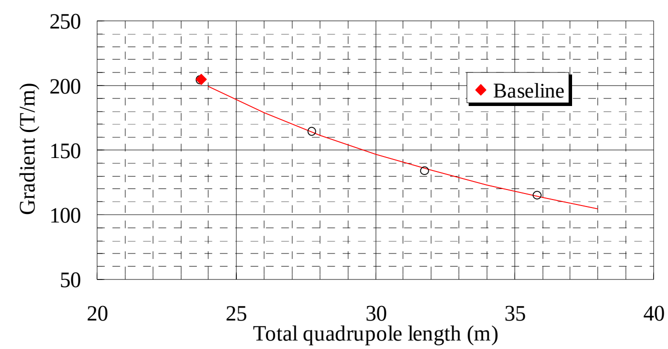
- We computed three lay-outs with LHC MB cable, of apertures 100, 120, 140 mm – still at the max of what can be obtained

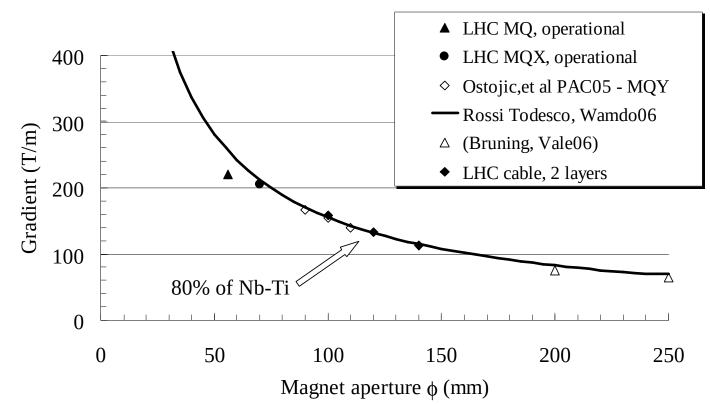


A FLOWCHART: TECHNOLOGY LIMITS

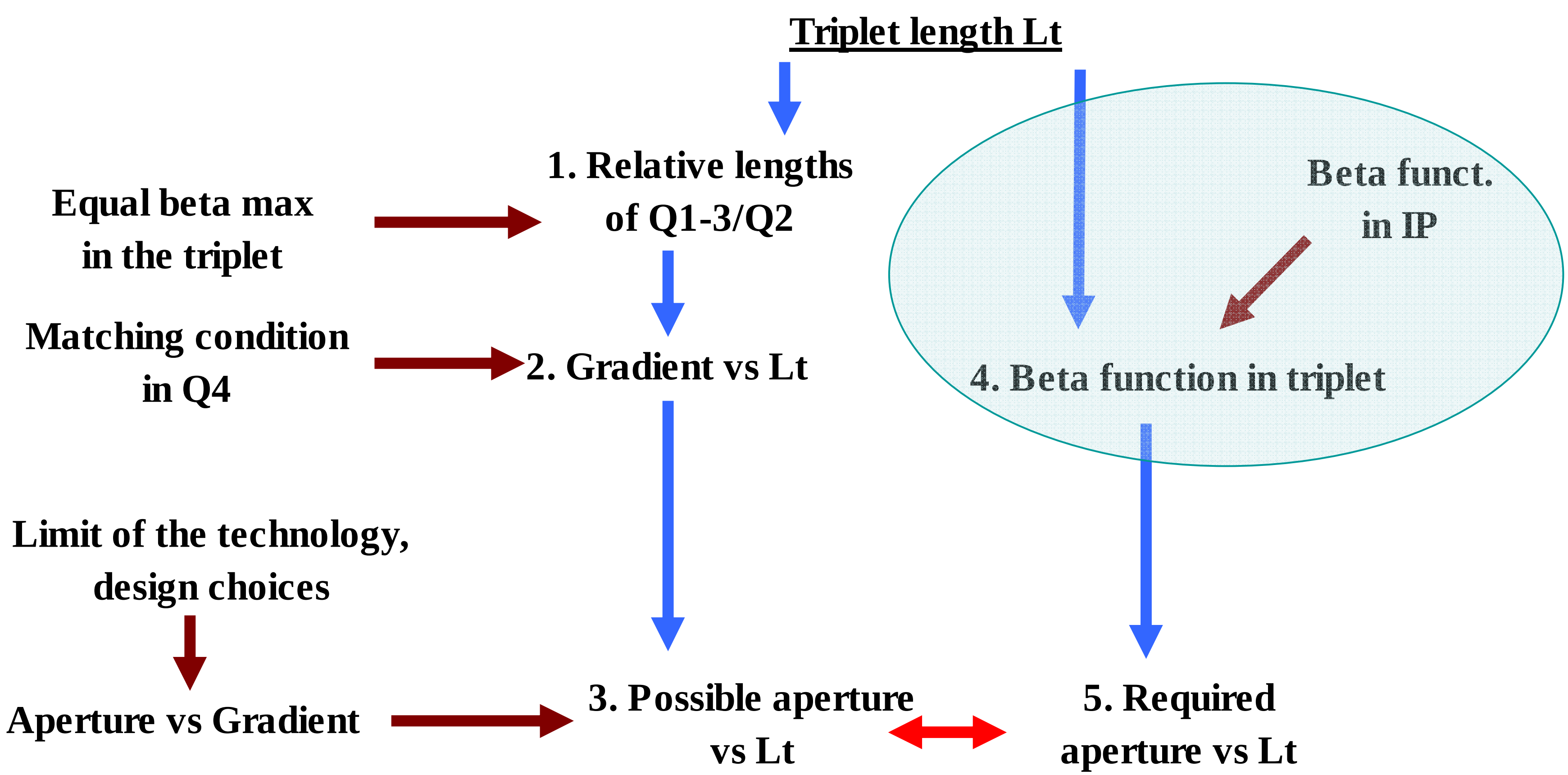
- We can now have aperture vs quadrupole length
  - With two layers Nb-Ti we can build focusing triplet of 30 m, 110 mm aperture – or 34 m, 130 mm aperture







A FLOWCHART: APERTURE REQUIREMENTS



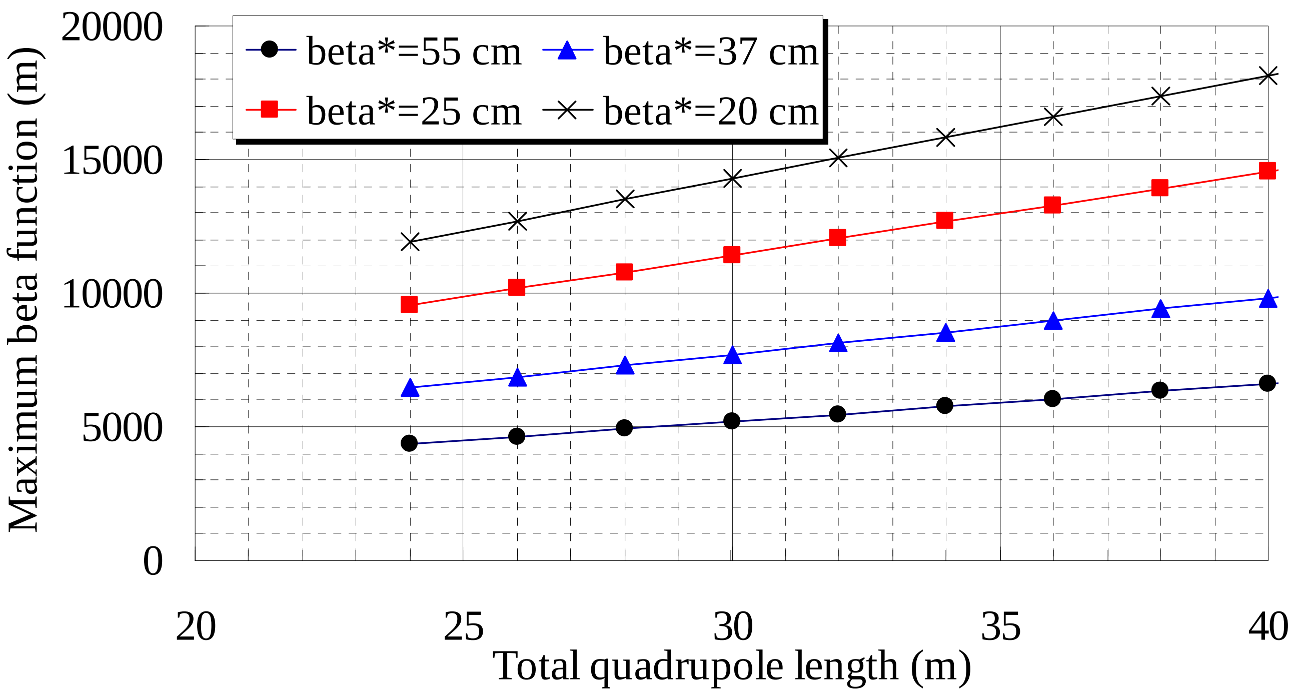
A FLOWCHART: APERTURE REQUIREMENTS

- Longer triplet will give larger beta functions !
  - Larger, but not terribly larger … we find a fit as

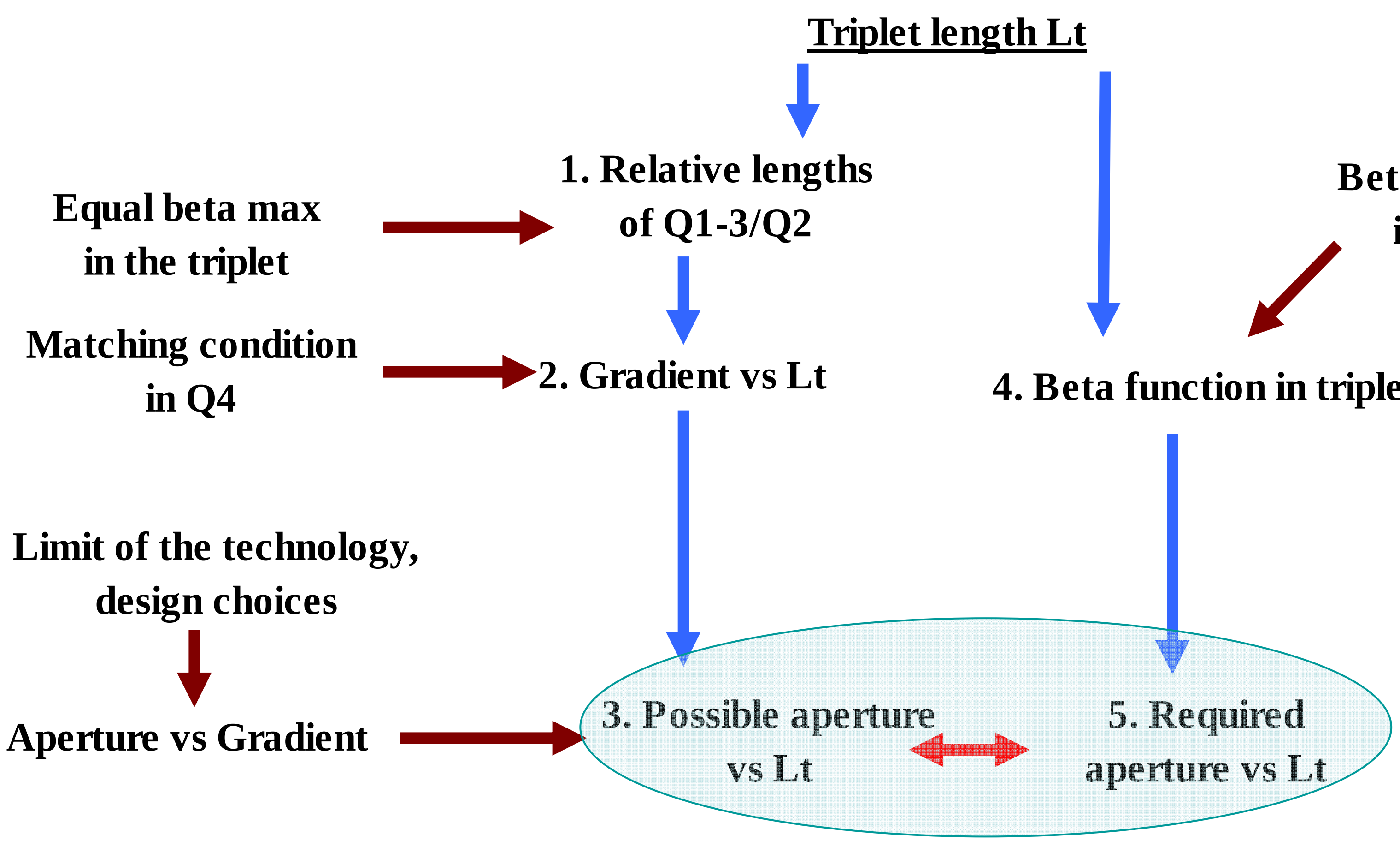
    a~77.5 m (where β^* is the beta in the IP)

    [E. Todesco, J. P. Koutchouk, Valencia06]

$$\beta_{\max} = \frac{l^{*2} + a l_q}{\beta^*}$$



A FLOWCHART: APERTURE REQUIREMENTS

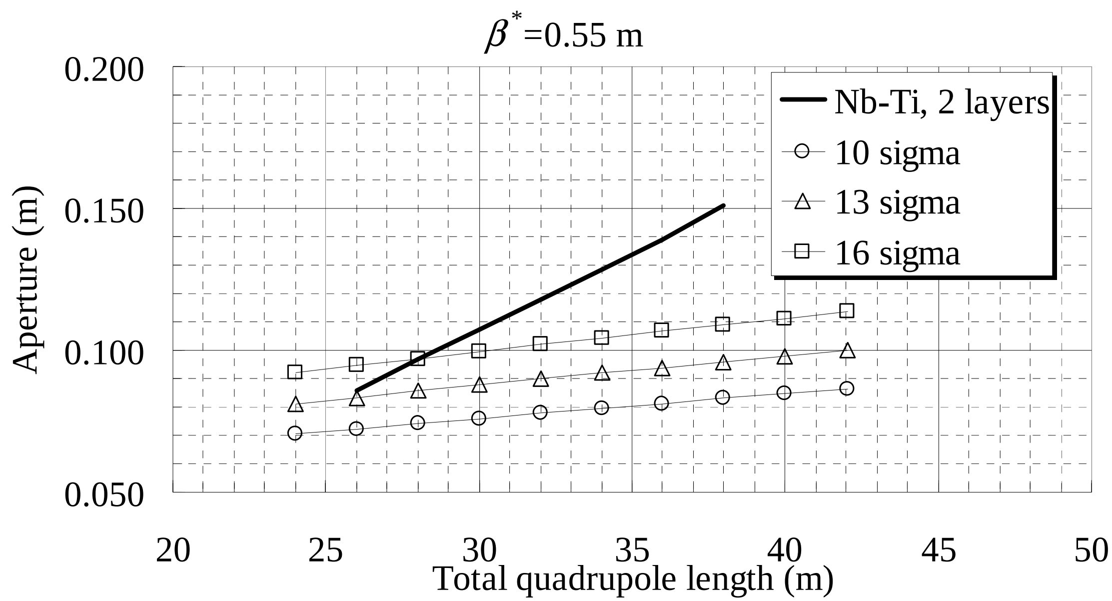


A FLOWCHART: APERTURE REQUIREMENTS

- β^*, β_{max} and the triplet length determine the aperture needs
  - 10 σ: the nominal

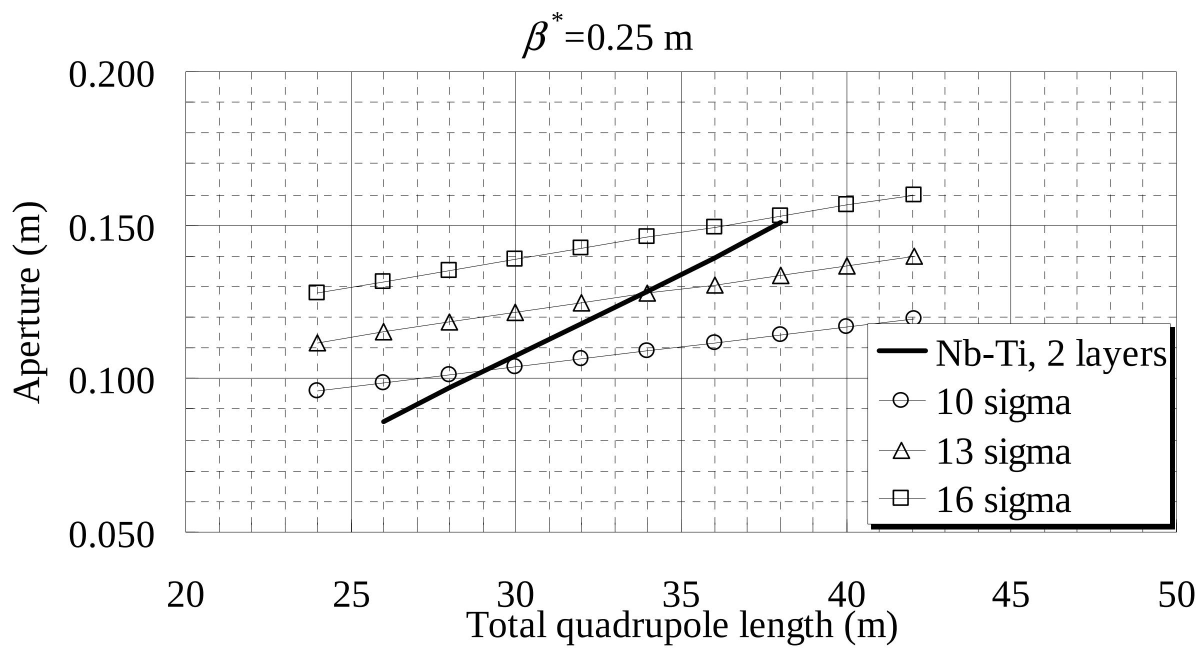
$$\phi = \phi_0 + \chi\phi_1\sqrt{\beta_{\max}} + \phi_2 \frac{l^* + l_t}{\sqrt{\beta^*}} + \phi_3 \frac{(l^* + l_t)^{3/2}}{\sqrt{\beta^*}}\sqrt{N_b k_b}$$

  - 13 σ: reduces the collimator impedance, and allowing a nominal beam intensity [E. Metral, '07] – 16 σ gives additional clearance
  - Example: a 28 m triplet with 95 mm aperture would leave 6 σ for collimation at β^*=0.55 m



A FLOWCHART: APERTURE REQUIREMENTS

- Going at β^*=0.25 m the aperture needs become larger
  - Example: a 34 m triplet with 130 mm aperture would leave 3 σ for collimation at β^*=0.25 m
  - Nice game … where to stop ?



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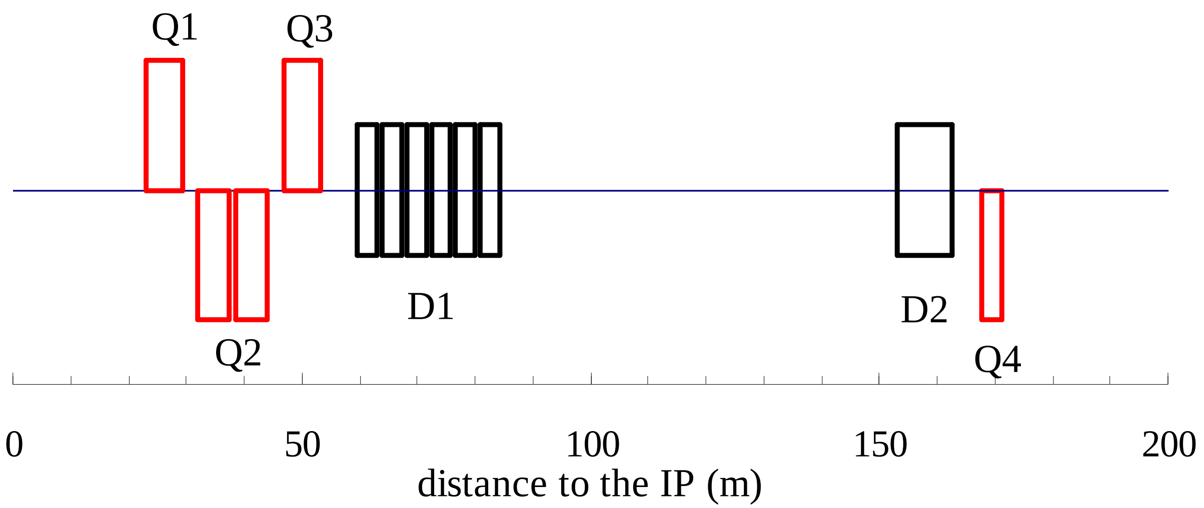
- Limits to long (and large) triplets
- Geometric aberrations
- Issues in magnet design

LIMITS TO LONG TRIPLETS

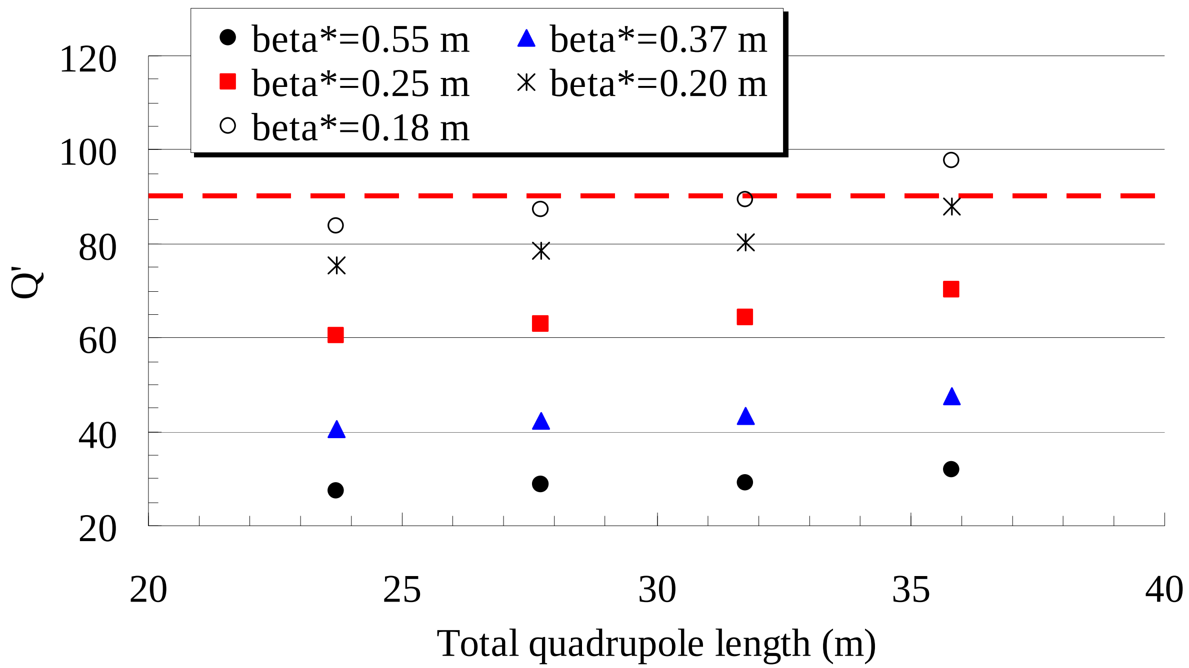
- Limits to long triplets: space ?
  - Present kicks in D1, D2 ~ 26 Tm
  - Separation dipole D2 is 9.45 m with 3.8 T – can go up to 36 Tm
  - D1 is 6 modules of warm magnets working at 1.28 T, with a margin of 18% - could be pushed away from IP of 15
    - is aperture enough ?
    - Otherwise, change D1 – in general, easy to recover space



LIMITS TO LONG TRIPLETS

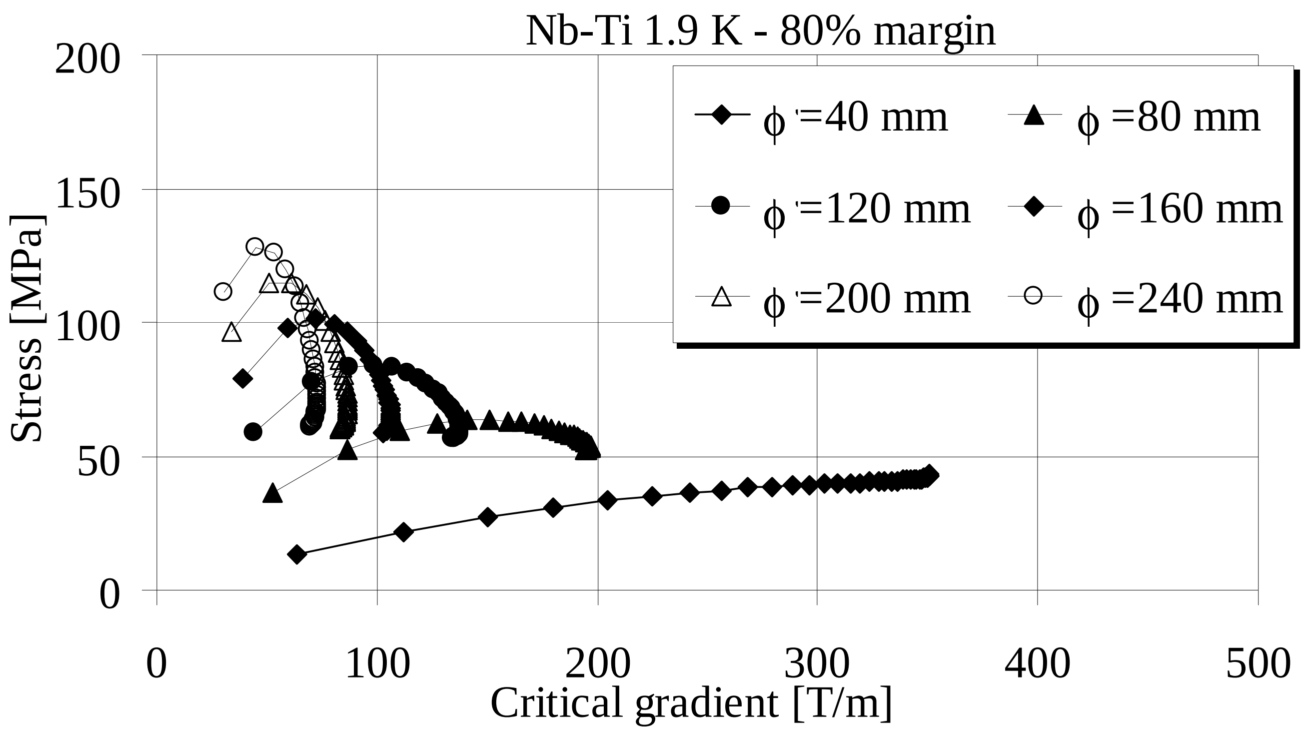
- Limits to long triplets: chromaticity ?
  - Hypothesis: two IP strong focusing, one IP at 1 m, the other at 0.5 m
  - The linear correction is saturated for β^*~0.20-0.18 m

limit of 90 per IP deduced from [S. Fartoukh, *LHC Project Report* **308**]



LIMITS TO LONG TRIPLETS

- Limits to long triplets: forces ?
  - Lorentz forces at operational field induce large stresses
  - Semi-analytical law [P. Fessia, F. Regis, E. Todesco, ASC 2006] gives values smaller than 150 MPa for apertures up to 250 mm – should not be a problem

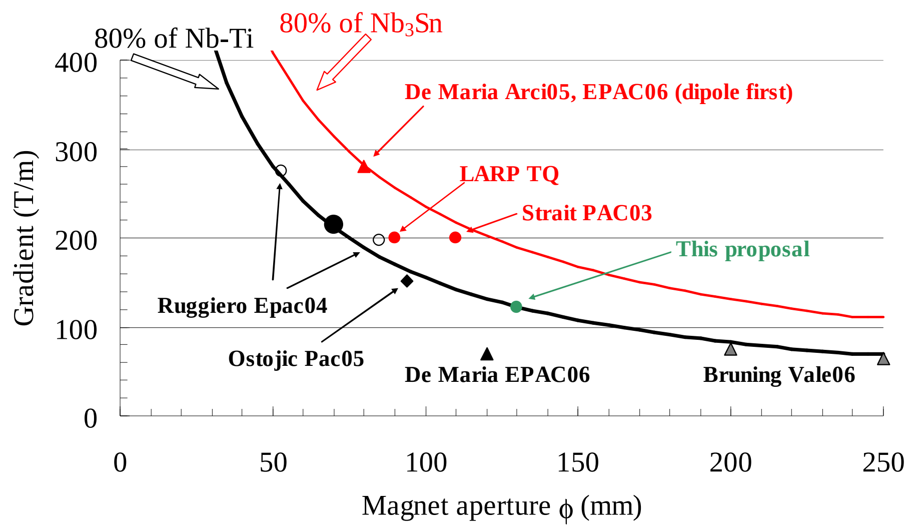


LIMITS TO LONG TRIPLETS

- Limits to long triplets: energy deposition ?
  - Larger and longer triplet could have a much higher energy deposition, for the same luminosity
    - Preliminary comparison of the baseline with a 10 m longer and twice larger triplet has been done [C. Hoa, F. Broggi, 2007]
    - The larger and longer triplet has a smaller (~-30%) impinging power in W/m (energy per meter of triplet)
  - Longer triplets will not give additional energy deposition
  - Study on scaling laws for energy deposition is ongoing

LIMITS TO LONG TRIPLETS

- We propose aperture for β^*=0.25 m with 3 σ for collimation
  - This would go up to β^*~0.18 m without collimation clearance
- This would give the following parameters
  - Total quadrupole length 34 m (+10 m w.r.t. baseline)
  - Triplet length (with gaps) 40.5 m
  - Operational gradient 122 T/m (20% safety factor on short sample)
  - Beta function in the triplet of 12600 m at β^* =0.25 m



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GEOMETRIC ABERRATIONS AND LARGE APERTURES

- In it has been observed that large beta functions in the triplet may lead to insufficient dynamic aperture

  [R. De Maria, O. Bruning, EPAC06]

  - Estimates based on tracking showed that there was a very strong reduction for an extreme case with $\beta_{\max}$=20000 m
  - The large β in the triplet is the cause of this effect – for instance first order terms in multipoles scale as

$$T_n \propto \int \frac{b_n(s) G(s) \beta^{n/2}(s)}{R_{ref}^{n-2}} ds \qquad\qquad T_n \propto \frac{\overline{b}_n G_I \beta_{\max}^{n/2}}{R_{ref}^{n-2}}$$

  and larger beta functions are amplified by the exponent …

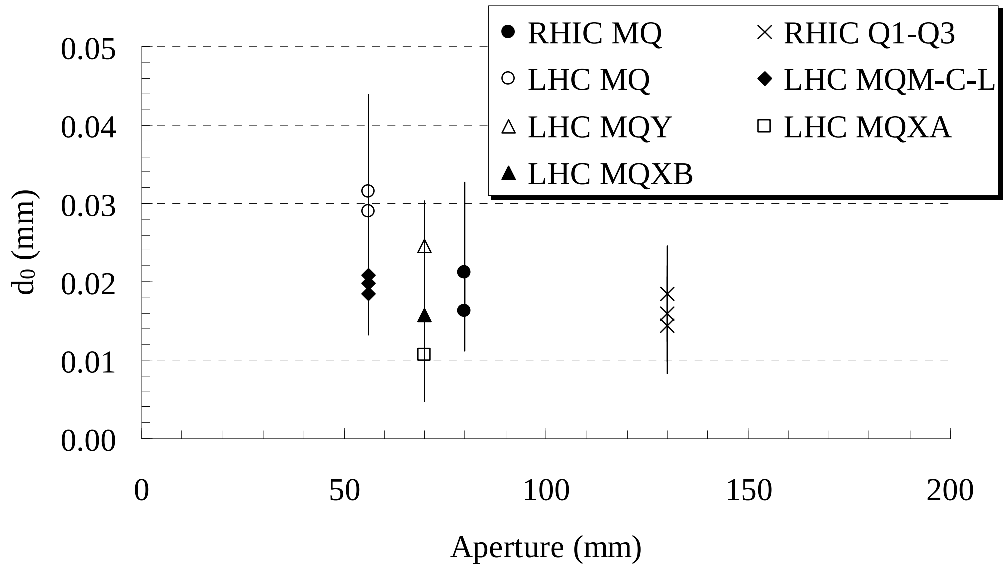
  - A crucial ingredient is the estimate of the field errors b_n

GEOMETRIC ABERRATIONS AND LARGE APERTURES

- Scaling law for field errors [B. Bellesia, et al, *Phys. Rev. STAB* **10** (2007) 062401]

$$\phi \rightarrow \bar{\phi} = \alpha\phi \qquad R_{ref} \rightarrow \bar{R}_{ref} = \alpha R_{ref} \qquad b_n \rightarrow \bar{b}_n = \frac{b_n}{\alpha}$$

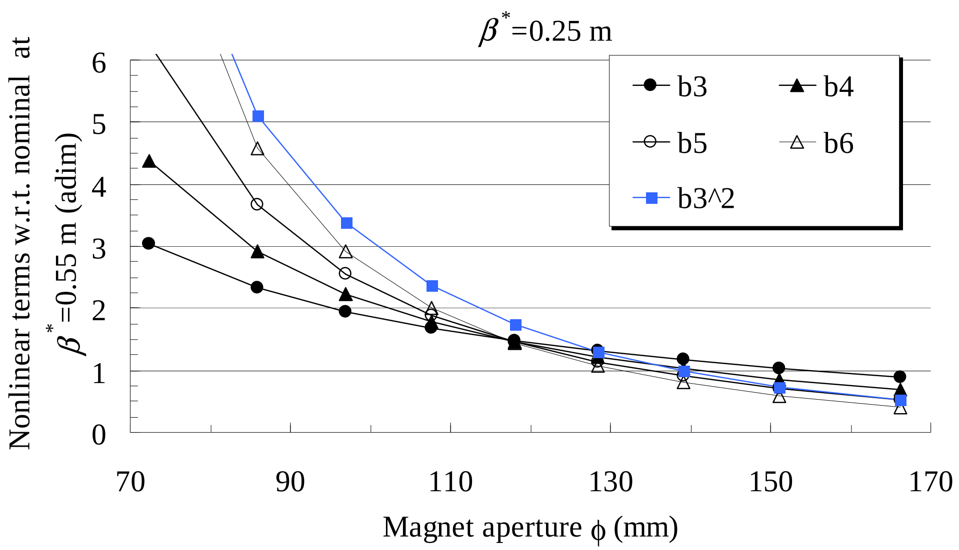
  - The hypothesis: field errors only due to cable positioning
  - Cable positioning independent of the aperture, based on LHC and RHIC data



Precision in coil positioning reconstructed from measurements

GEOMETRIC ABERRATIONS AND LARGE APERTURES

- Using the scaling for field errors, we evaluated the aberrations at β^*=0.25 m as a function of the triplet aperture
- We normalized them to the values of the baseline at β^*=0.55 m
- A triplet of 90 mm aperture has significantly larger aberrations
- A triplet of 130 mm has only 30% more



- Cross-check: solution of [R. De Maria, O. Bruning, EPAC06] would give a factor 3-7 larger aberrations

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ISSUES IN MAGNET DESIGN MAIN FEATURES

- Main parameters compared to other LHC quadrupoles

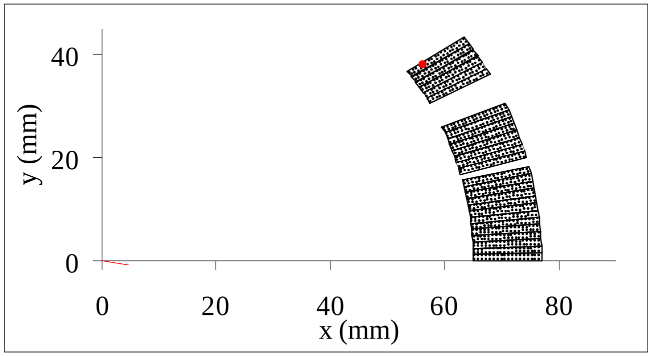
Magnet	Aperture (mm)	Length (m)	Coil (mm^2)	Operational Gradient (T/m)	Operational Current (A)	Operational Peak field (T)	Margin	Grading (%)
MQ	56	3.10	5014	223	11870	6.9	0.80	0
MQY	56	3.40	5674	160	3610	6.1	0.82	43
MQXA	70	6.37	8496	215	7149	8.6	0.80	10
MQXB	70	5.50	5395	215	11950	7.7	0.84	24
MQXC	130	7.8/9.2	10145	121	11400	8.4	0.79	27

- Large aperture ? RHIC MQX: 130 mm aperture, 50 T/m at 4.2 K, 12 mm width coil

- Cable needed to wind

  one dipole unit length is enough

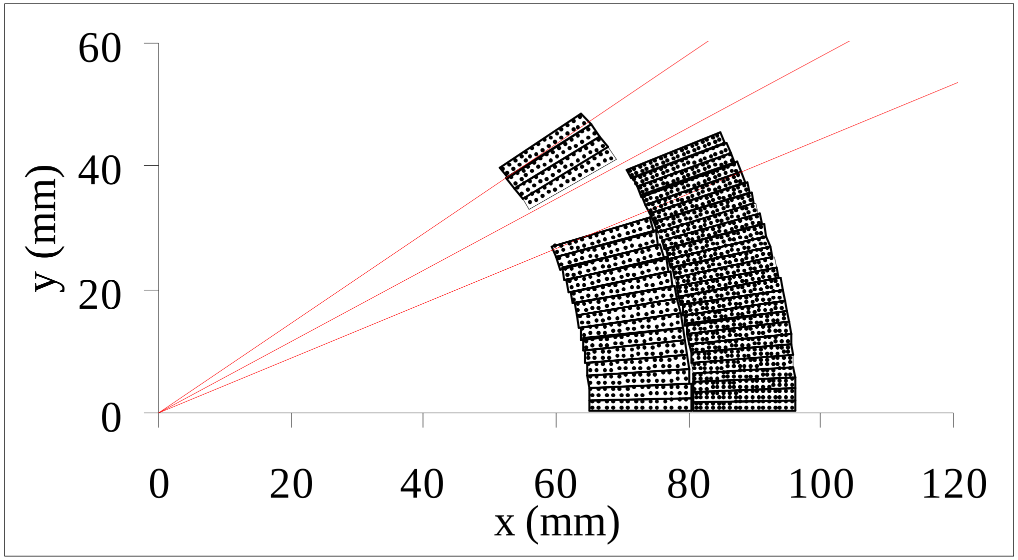
	length (m)	Inner layer n turns (per pole)	Inner layer pole length (m)	Outer layer n turns (per pole)	Outer layer length (m)
MQXC	9.2	18	331	26	478
MQXC	7.8	18	281	26	406
MB	14.3	15	429	25	715



RHIC large aperture quadrupole

ISSUES IN MAGNET DESIGN – FIELD QUALITY

- Field quality is critical at nominal field – optimization includes iron saturation, persistent currents not an issue
- Coil designed on the [24°,30°,36°] lay-out – 25 mm thick collars
- Probably, a first iteration will be needed to fine tune field quality
  - Thick mid-plane shims have been included from the beginning, so that can be varied in both directions
- At least three identical models should be built to assess the random components
  - Are critical !!



ISSUES IN MAGNET DESIGN – PROTECTION

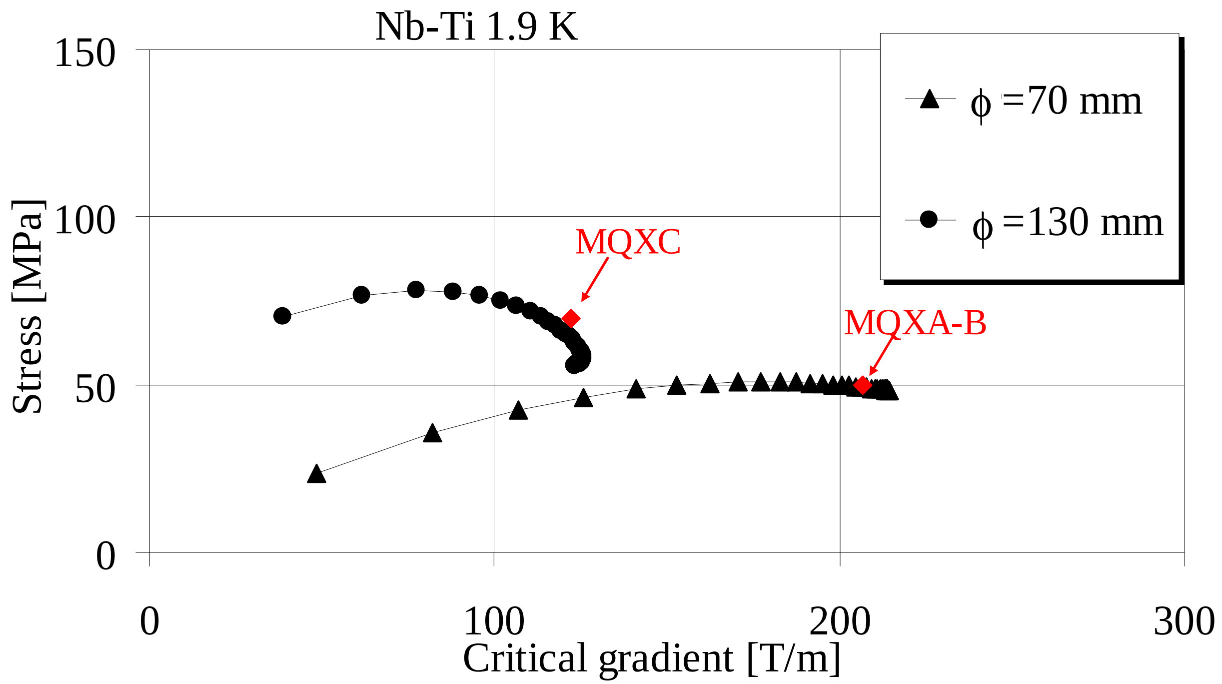
- This MQXC is longer and larger than the previous ones
  - Inductance similar to MQY, MB, MQXA
  - Operating current similar to MB, MQ, MQXB
  - Stored energy is 5 MJ: twice MQXA – 50% larger than one aperture of an MB

Magnet	Current (A)	Inductance (mH)	Energy (MJ)
LHC MB	11850	99	6.93
LHC MQ	11870	6	0.39
LHC MQY	3610	74	0.48
LHC MQXA	7150	90	2.30
LHC MQXB	11950	19	1.36
LHC MQXC	11400	76	4.93

  - Preliminary hot spot temperature evaluations show that the order of magnitudes are similar to the MB
    - Time for firing quench heaters to avoid hot spot larger than 300 K must be not larger than 0.1 s [M. Sorbi, Qlasa code] challenging, but feasible

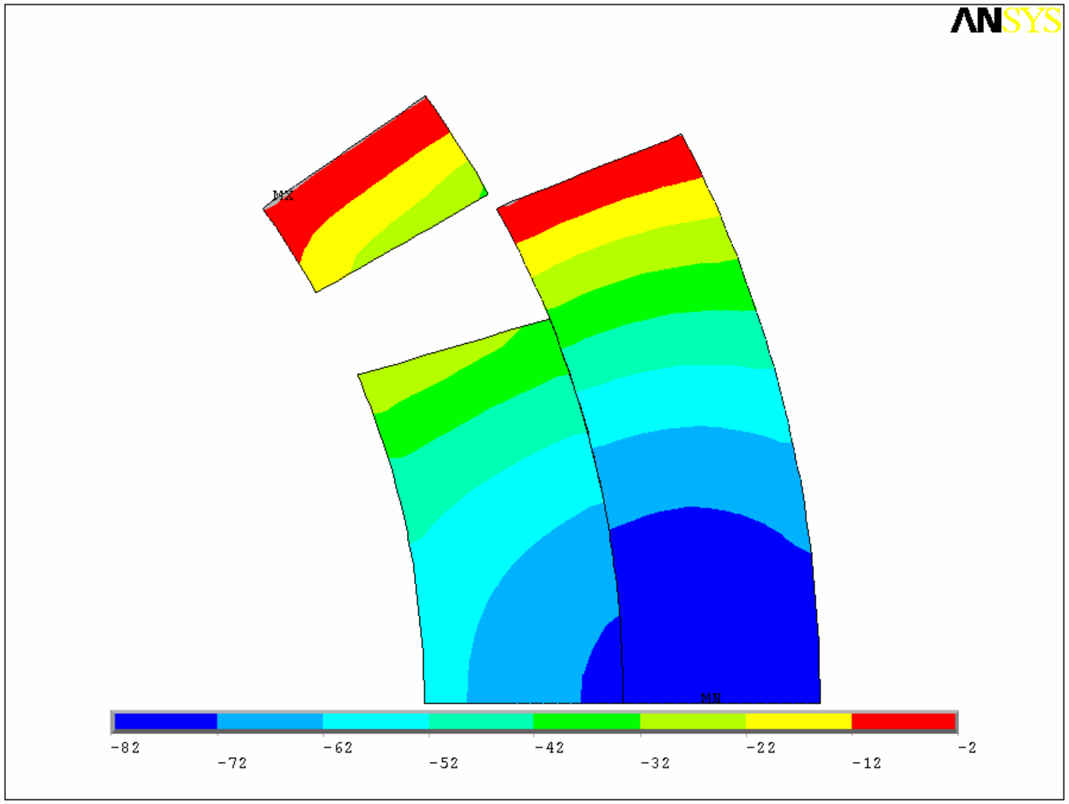
ISSUES IN MAGNET DESIGN – FORCES

- According to analytical model
  - Lorentz forces induce a stress in the coil of 70 MPa, i.e. 40% more than for the MQXA-B (50 MPa)
  - Does not look so critical, but mechanical structure should be carefully designed



ISSUES IN MAGNET DESIGN – FORCES

- Computations using FEM model [F. Borgnolutti, E. Todesco PAC07]
  - MQXC: ~80 MPa
  - MQXA: ~ 70 MPa, MQXB: ~ 50 MPA



CONCLUSIONS

- Proposed lay-out aims at
  - β^*=0.25 m with 3 σ clearance for collimation
  - β^*~0.18-0.20 m without clearance, reaching the linear chromaticity correction limit
  - The clearance should allow keeping geometric aberrations under control (we have a β_{max} =12600 m)

- The lay-out is simple
  - One aperture: 130 mm
  - One gradient: 122 T/m
  - One power supply – operational current 11400 A
  - One cross-section: two layers with LHC MB cable
  - Two lengths: 7.8, 9.2 m – moderate increase of triplet length w.r.t. baseline (+30%, i.e. from 30 to 40 m)

CONCLUSIONS

- Implications of phase-one upgrade on LARP and Nb_3Sn R&D
  - Phase two upgrade (the 'real' one) goals and schedule are not changed
  - Nb_3Sn R&D should be pursued with all efforts
    - The proof of a long prototype is fundamental
    - If we had available Nb_3Sn magnets today, we would use them
- Two main implications
  - Moving D1 $\rightarrow$ the goal of 200 T/m disappears
    - 200 T/m is the force needed for a 25 m triplet at 23 m from IP
  - The optimal aperture will be 130 mm (at least)
    - 130 mm corresponds to the aperture of the outer layer of TQ
    - Stresses for these large aperture magnets can be critical
    - Studies are ongoing and will be presented in PAC and MT-20